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Quantitative assessment of in-vehicle-generated EMI in a real-world environment

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QUANTITATIVE ASSESSMENT OF IN-VEHICLE-GENERATED EMI IN A REAL-WORLD ENVIRONMENT

By

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THESIS

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DEDICATION

I dedicate this thesis to my beloved parents

for their continuous support and encouragement.

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FCC	Federal Communications Commission
EMI	Electromagnetic Interference
VHF	Very High Frequency
EUT	Equipment Under Test

ABSTRACT

QUANTITATIVE ASSESSMENT OF IN-VEHICLE-GENERATED EMI IN A REAL-WORLD ENVIRONMENT

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Interference generated by electronic equipment inside a vehicle can interfere with radio reception even though that equipment is in compliance with FCC standards. The result of that interference is an undesired reduction in radio coverage at frequencies where the interference exists.

The contribution of this work is a method for measuring electromagnetic interference (EMI) generated by in-vehicle electronic equipment when external radiation is present. The approach is to identify regions in the spectrum where externally generated signals exist and then to bypass those regions when measuring interference from in-vehicle-equipment. Using the FCC database of licensed radiation sources to identify those regions will not achieve the desired goal. An analysis of the received spectrum is used to assess the presence of signals. Trade-offs between measurement accuracy and the time to perform the measurements are given, along with information on measurement repeatability.

CHAPTER 1

INTRODUCTION

Contemporary vehicles are being populated with an increasing number of computing devices, and each of these devices has the potential to interfere with its own operation as well as the operation of other devices in the vehicle. To help minimize the negative effects of interference, the Federal Communications Commission (FCC) has imposed standards on the amount of interference that any given device can radiate, and devices installed in vehicles generally meet those standards. As a result, interference from one device seldom causes another device to malfunction outright, although that interference can degrade the performance of some devices such as radio receivers. It is the detection of that low-level interference that is the topic of this paper.

To mitigate the effects of interference on receiver performance, several approaches are used. One of the most important approaches is to use ferrite beads on all wires and cables connected to electronic devices. These ferrites tend to dampen spurious radiation that would be launched along the wire in the absence of the ferrites. Experience has shown that for typical installations involving in-compliance devices having ferrite beads connected to all cabling, the interference generated does not degrade the performance of a radio receiver. However, even if only one ferrite bead is missing, and there are often quite a few in a typical installation, significant degradation of radio performance can result. Although visual inspections can be performed to detect problems like missing ferrite beads, the only truly reliable way to detect improper installation is by performing interference measurements.

This paper concentrates on a technique that has been developed that allows quick and reliable EMI check of in-vehicle electronic equipment. The main goal of this technique is to detect EM shielding problems, such as missing ferrite beads that can cause interference with other sensitive electronic devices. Further, this technique is designed in such a way that the test can be performed without requiring a specialized facility, such as shielded anechoic chamber.

The work presented here is associated with what is known as Project54 [1] which is an effort to network electronic devices in emergency vehicles. The resulting system entails multiple network controllers that connect devices such as the VHF radio transceiver, video camera, light bar, radar and other equipment to an in-vehicle personal computer. This configuration affords considerably greater efficiency and safety for controlling the devices, such as enabling voice activation of devices, although having so many networked devices does exponentially increase the possibility of creating interference that might degrade radio reception.

Interference measurements performed outside a shielded enclosure necessitates bypassing frequencies where external radiation is present so that those sources do not contaminate the measurement process. Because the environment in which these measurements are to be performed can contain unlicensed radiation sources, such as radiation from nearby vehicles and equipment, the bypassing of local licensed radiation source frequencies determined from the FCC Frequency Assignment Database [4] would not be effective. The approach that has been proven effective here is to iteratively scan through the band of interest to identify, and subsequently bypass, frequencies where signals are present when the EUT is turned off. Determining the locations of man-made radiation sources requires more than a simple threshold test due to the variability in the noise floor in typical environments.

The intermittent nature of radio transmissions in the VHF emergency band poses a challenge in this process, although a judicious selection of measurement parameters (i.e., scan range, frequency step size, resolution bandwidth, and signal and noise thresholds) enable the measurements to be performed accurately and in a reasonable amount of time.

The choice of the frequency step size and the resolution bandwidth affect the precision of the measurements as well as the time it takes to perform a measurement. Trade-offs between these measurements are addressed in subsequent sections of this thesis.

CHAPTER 2

STRATEGY FOR BYPASSING EXTERNAL RADIATION SOURCES WHEN MEASURING EMI

2.1. Overview

As stated previously, the approach to measuring in-vehicle interference without requiring a shielded anechoic chamber is made possible by identifying and then bypassing frequencies that contain signals from man-made sources. Were it not for the variable nature of ambient noise, this process could be readily achieved by a single scan of the frequency band of interest, where signals above a set threshold would be bypassed. However, because that background noise can vary considerably from one location to the next, the task of bypassing man-made frequencies requires first identifying the noise floor in a particular environment. Determining that noise floor requires an iterative process, where each iteration eliminates successively weaker external signals until a spectrum with the statistical properties of noise alone remains. Because the frequency bypass process is to be performed when a human operator is waiting, the challenge is to not only identify the noise floor, but to do it in a timely manner.

This chapter begins with a discussion of the statistics of spectra containing both signals and noise, and of those having noise alone. Then, the bypass process that uses spectral statistics is described along with the trade-offs between accuracy, bandwidth and convergence time. The chapter ends with results of the bypass process on real spectra obtained from a range of electromagnetic environments.

2.2. Statistical Properties of Signal Spectra

The approach for developing the frequency bypass scheme involved computer modeling using both deterministic statistical spectra as well as measured spectra. The rationale behind this two-fold approach was to demonstrate that the solution will work in a broad range of environments, and not just in the limited number of environments measured for this study.

The environmental spectrum was modeled as a mixture of ambient noise and man-made signals. Ambient noise was modeled as Gaussian noise with mean (μ) of -110 dBm and standard deviation (σ) of 0.5 dB. Man-made signals were generated based on a normalized signal with log-normal amplitude distribution with mean of 0 and standard deviation of 0.8. Both signals were randomly mixed together forming a signal vector containing 90% ambient noise samples and 10% coherent noise samples. These percentages were chosen because they are typical of a signal-rich spectrum. The length of the resulting vector is equal to the length of original ambient noise vector in order to model a realistic noise formation where man-made signals overlay original ambient noise at random frequencies. It should be noted that the statistical properties described are given for a frequency spectrum and not as a time function.

Figure 2.1 shows probability density functions for the original ambient, man-made and resulting mixture signals.

The model also operates under the assumption that man-made signals with magnitudes less than or equal to maximum magnitude of the ambient noise cannot be detected using envelope detection techniques. Therefore, in figure 2.1 the distributions do not overlap, and the ambient noise distribution ends where the man-made noise distribution starts. The task of identifying signals where the distribution of the man-made signals overlaps ambient noise distribution is out of the scope of this paper and importantly, it does not impact the results presented here.

In the actual application, the statistical parameters of both distributions are unknown. The parameters of the combined distribution can only be obtained through measurements. In this situation, the task of removing man-made signals from the environmental noise spectrum requires estimating the parameters of the original ambient noise amplitude distribution. The threshold for removing man-made signal from the spectrum must be chosen such that after removing all the external components, the parameters of the remaining amplitude distribution will become the best estimates of the original ambient noise. The threshold must be set outside the original ambient noise distribution however, so that only signal components will be removed. The shaded area in figure 2.2 shows the threshold that removes man-made signals yet preserves the original ambient noise statistical parameters. The general expression for the threshold based on the original ambient noise statistical parameters is

$$Th = \mu + n_{\sigma} \cdot \sigma \qquad (2.1)$$

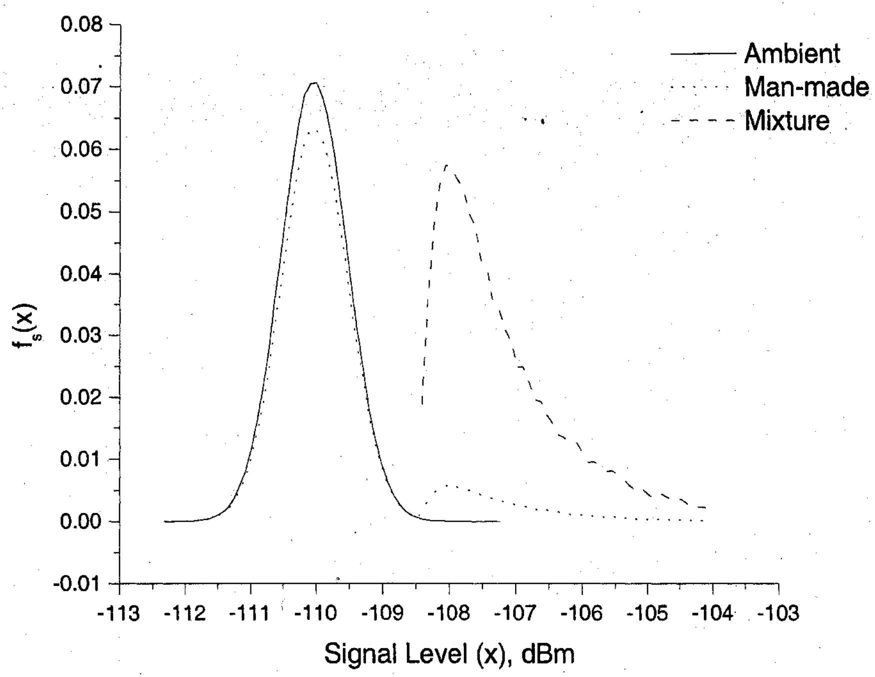

Figure 2.1. Modeled amplitude distribution functions

where μ and σ are the ambient noise mean and standard deviation, and n_σ is a standard deviation coefficient. Therefore, using different values of n_σ in expression 2.1 will control how well the parameters of ambient noise will be estimated after applying the threshold.

The best estimate of the ambient noise can be achieved by minimizing the estimation errors for the mean and deviation defined as follows:

$$E_\mu = \mu - \mu' \qquad (2.2)$$

$$E_\sigma = \sigma - \sigma' \qquad (2.3)$$

Where $\mathbf{E_\mu}$ is the estimation error of the original ambient noise mean $\boldsymbol{\mu}$ using its estimate $\boldsymbol{\mu}'$ and $\mathbf{E_\sigma}$ is the estimation error of the original ambient noise standard deviation $\boldsymbol{\sigma}$ using its estimate $\boldsymbol{\sigma}'$ (figure 2.3).

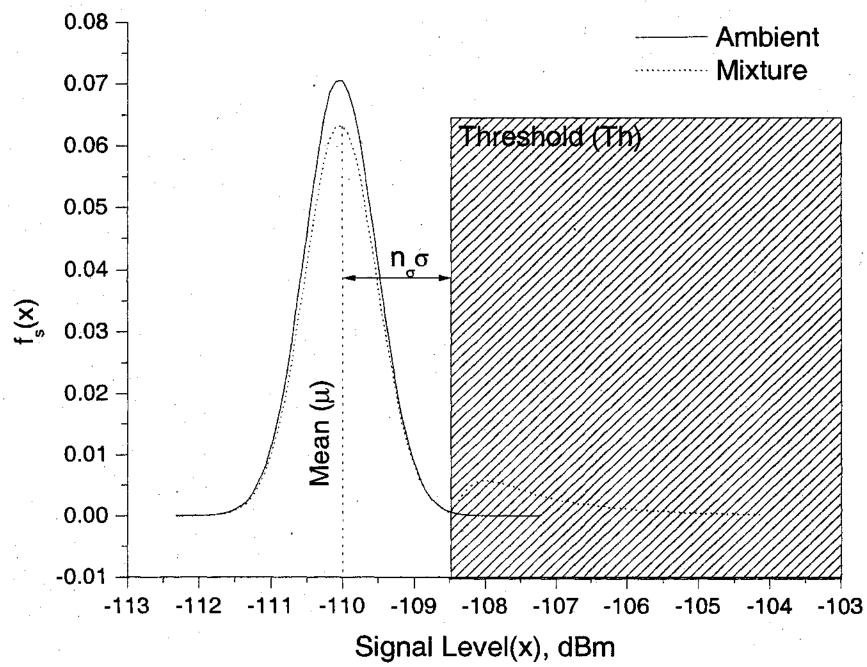

Figure 2.2. Man-made signal bypass threshold

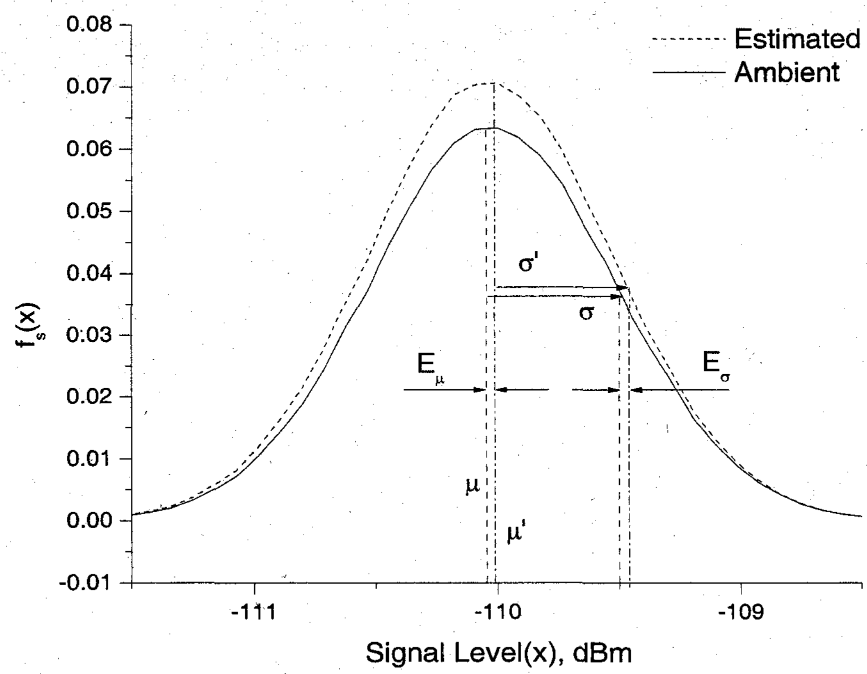

Figure 2.3. Ambient noise amplitude distribution parameter estimation errors

As shown in figure 2.4 the majority (99%) of the Gaussian distribution lies within $3\boldsymbol{\sigma}$ of its mean ($\boldsymbol{\mu}$). Assuming that the parameters of the original ambient noise are known, the threshold that will remove the majority of the man-made noise will be $3\boldsymbol{\sigma}$ above the ambient noise mean or:

$$\mathrm{Th} = \mu + 3\sigma \qquad (2.3)$$

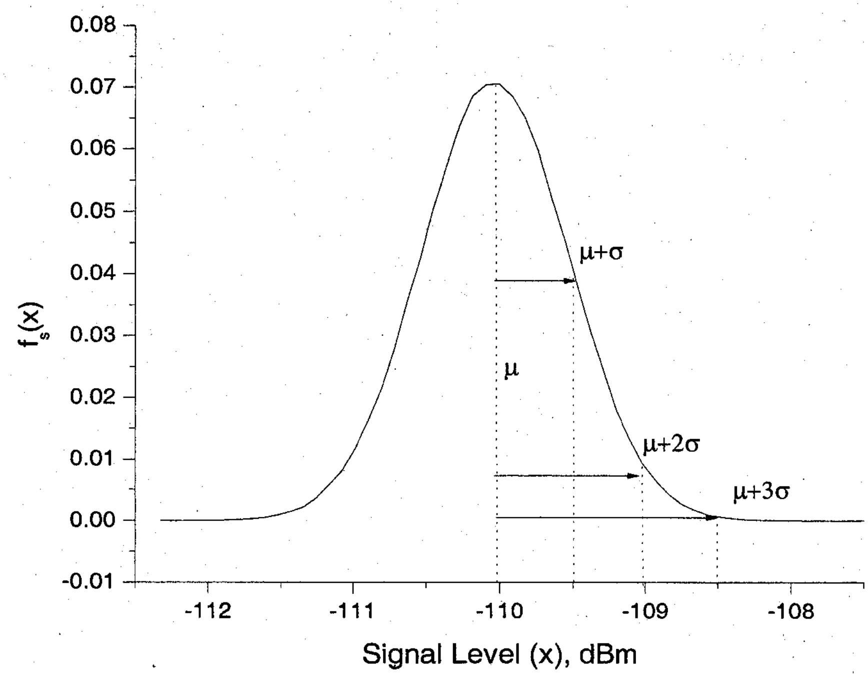

Figure 2.4. Gaussian noise amplitude distribution properties

In order to validate the effectiveness of (2.3), different threshold values were used in the modeling scheme, where the thresholds were calculated using $n_\sigma = 1.5$ in integer steps.

The estimated parameters were compared to idealized parameters used to model the original ambient noise. The resulting noise distribution estimates are shown in figure 2.5.

As is seen in figure 2.5, the 3σ threshold gives the closest estimation of the original ambient noise distribution.

Table 2.1 shows the estimates of the noise means and deviations and estimation errors related to the original parameters. With $n_\sigma = 3$, the calculated threshold removes 101% of the man-made signals introduced into original ambient noise. One percent above 100% indicates that 1% of the original ambient noise amplitude distribution was removed as is evident in figure 2.4.

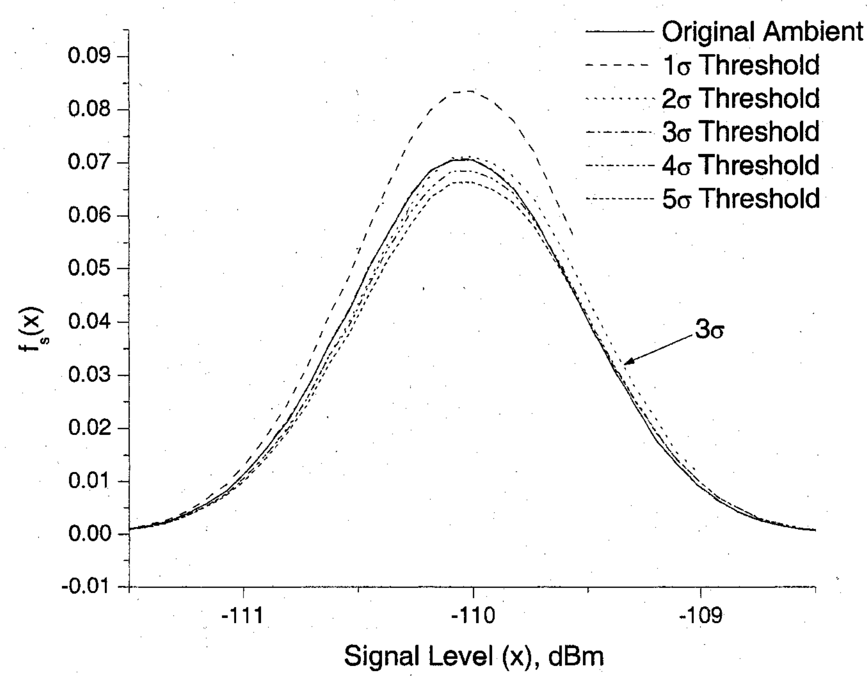

Figure 2.5. Ambient noise amplitude distribution estimates

n_σ	μ', dBm	σ', dB	E_μ, dB	E_σ, dB	Man-made noise removed, %	Threshold, dBm
1	-110.14	0.40	-0.14	0.10	242.73	-109.50
2	-110.03	0.47	-0.03	0.03	120.42	-109.00
3	**-110.00**	**0.50**	**0.00**	**0.00**	**101.23**	**-108.50**
4	-109.96	0.56	0.04	-0.06	78.73	-108.00
5	-109.90	0.66	0.10	-0.16	52.21	-107.50

Table 2.1. Estimated ambient noise parameters

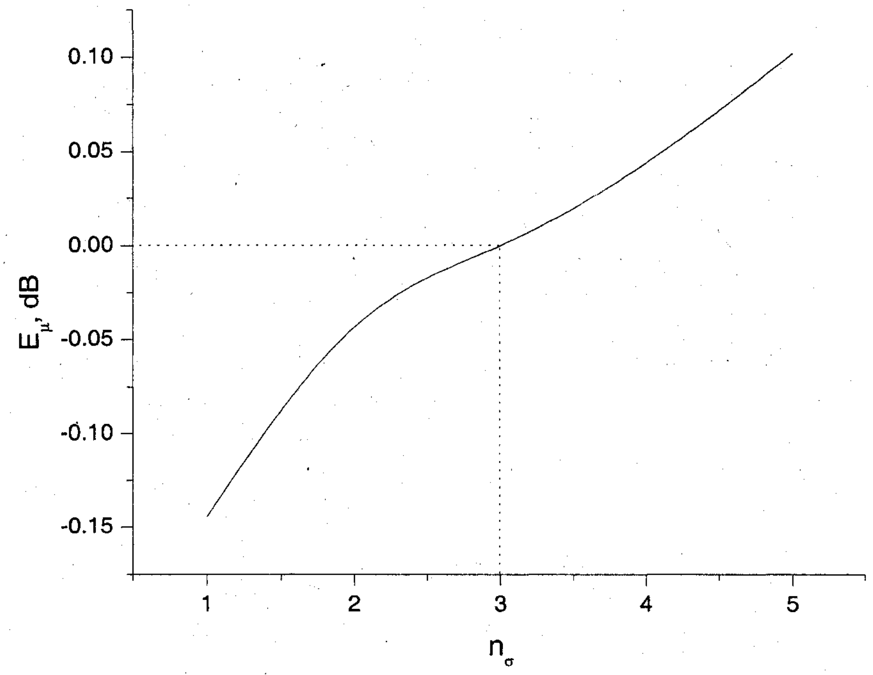

Figure 2.6. Ambient noise mean estimation error

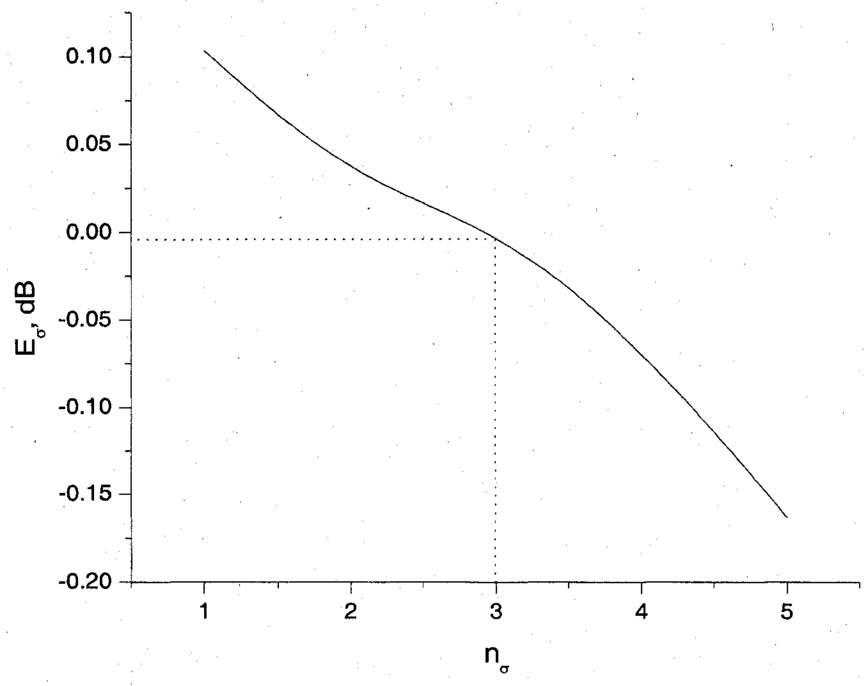

Figure 2.7. Ambient noise standard deviation estimation error

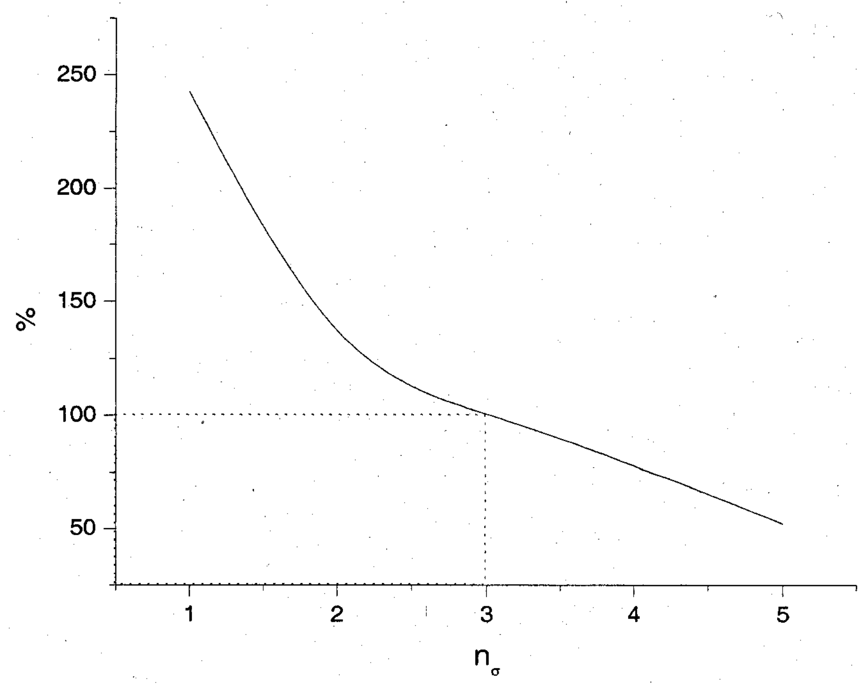

Figure 2.8. Amount of man-made noise removed from the mixed noise distribution

In actual measurements, the threshold computation cannot be based on the original ambient noise parameters, since they are not known initially. However, operating under the realistic assumption that the amount of man-made noise is significantly less than the amount of the original ambient noise, approximating the ambient noise is still possible. The effect of the amount of man-made signal on measurement quality is discussed in chapter 4.

In this case, the bypass threshold must be calculated using the environment noise mean value. Since the statistical distribution of a spectrum is a mix of the ambient noise and man-made signals, the mean value will be higher than the original ambient noise mean. If it is assumed that both noise means do not change with time, then the following expressions are applicable:

$$\mu' = p_1 \mu_1 + p_2 \mu_2 \qquad (2.4)$$

$$p_1 + p_2 = 1 \qquad (2.5)$$

$$p_1 = N_1/N \qquad (2.5)$$

$$p_2 = N_2/N \qquad (2.6)$$

$$N = N_1 + N_2 \qquad (2.7)$$

Where μ' is the mixed distribution signal mean, N_1 and N_2 are numbers of the signal level samples for each of the distributions, and N is the total number of the samples. Therefore, for the environmental noise with 10% of the man-made signals, the mean value will be as follows:

$$\mu' = 0.9\,\mu_b + 0.1\,\mu_{mm} \qquad (2.8)$$

In this case, the deviation of the combined distribution will be dependent on its mean value. As the percentage of man-made signals increases, the deviation will also increase towards man-made noise deviation value, as defined by:

$$\sigma' = \sqrt{\frac{1}{N}\sum (x_i - \mu')^2} \qquad (2.9)$$

The calculated threshold will also be greater than the one calculated for original ambient noise as shown in figure 2.8.

This threshold will remove only certain amounts of the man-made signal (approximately 24% for a **3σ** threshold) when applied only once. This threshold must be recalculated based upon a modified distribution and then applied again. A number of iterations have to be performed in order to obtain a value close to the ambient noise estimate.

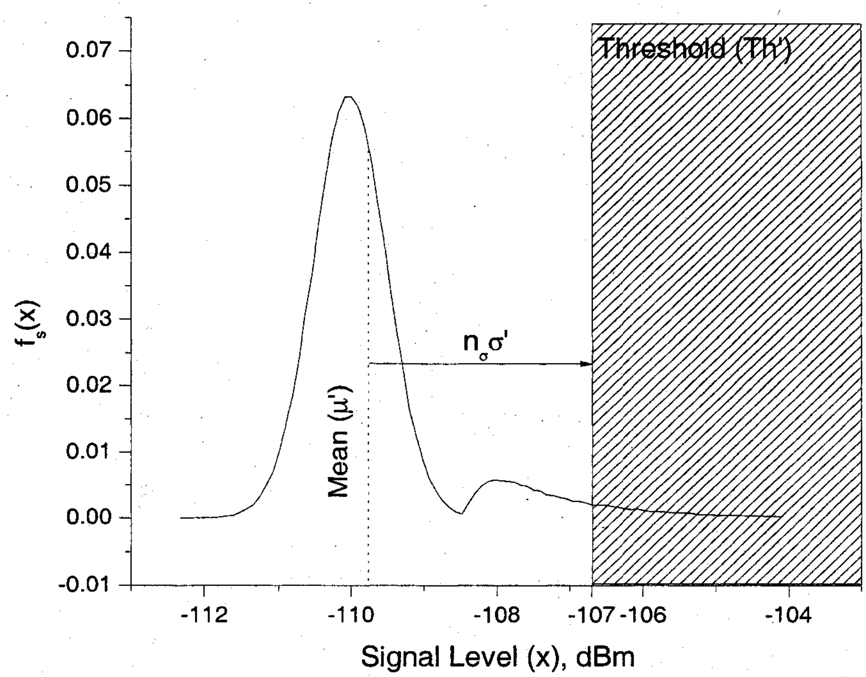

Figure 2.9. Bypass threshold estimate applied to mixed noise distribution

The number of iterations required to reach this value depends on the choice of the threshold. As shown earlier in this chapter, expression 2.3, using 3σ, gives the best ambient noise parameter estimates.

With each iteration, the threshold will become lower and closer to the one calculated for the original ambient noise. Consequently, when the estimated distribution approaches the original noise distribution, the calculated threshold will become the original threshold estimate and will not remove any of the original noise components.

Figure 2.9 illustrates the changes in the combined distribution as the threshold is recalculated with each iteration. As the threshold value becomes lower, the distribution becomes narrower as man-made signals are eliminated, causing the resultant distribution to become closer to that of ambient noise alone. On the sixth iteration, the estimated and the original distributions become nearly identical (see figure 2.10). Their parameter estimation errors become very small and the thresholds become almost equal, with less than 0.02 dB error (table 2.2). The percentage of the removed man-made signal (relative to the original man-made signal level) increases from 24% on first iteration to 101% on the

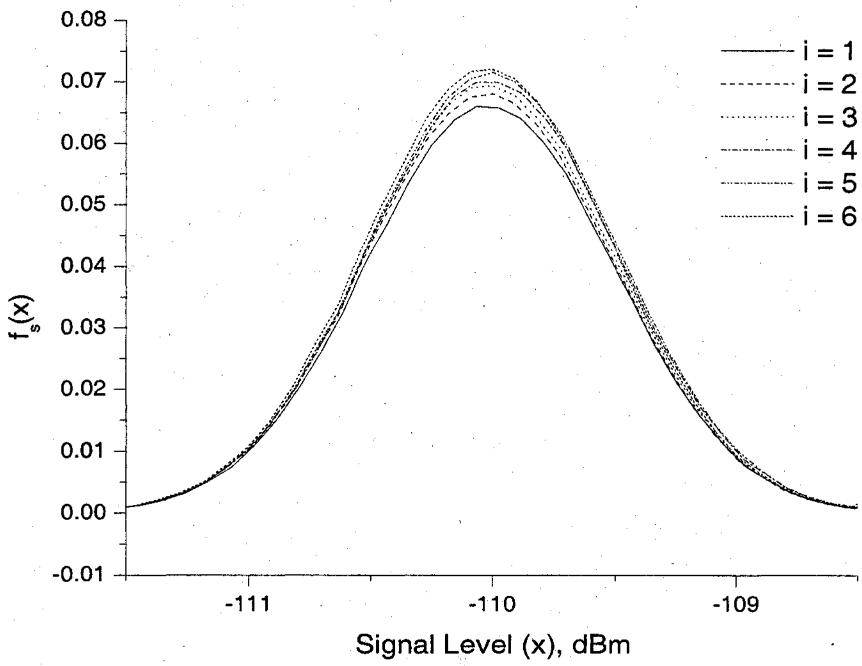

Figure 2.10. Ambient noise distribution estimate

final iteration, as is shown in table 2.1. After the estimation errors have been minimized, each subsequent iteration may still remove some amount of the original ambient noise,

i	μ', dBm	σ', dB	E_μ, dB	E_σ, dB	Man-made noise removed, %	Threshold, dBm
1	-109.816	0.801	0.18	0.30	23.736	-106.71576
2	-109.885	0.682	0.12	0.18	47.948	-107.4144
3	-109.933	0.604	0.07	0.10	67.75	-107.8401
4	-109.969	0.546	0.03	0.05	84.336	-108.1213
5	-109.996	0.504	0.00	0.00	98.544	-108.3318
6	-110.001	0.497	0.00	0.00	101.162	-108.4842

Table 2.2. Estimated parameters of the ambient noise on each iteration using 3σ threshold

which will be within a fraction of a percent. This is the reason for restricting the number of iterations depending on the measured noise properties. As is shown in a subsequent section of this chapter, the number of iterations necessary when processing real environmental noise can be fewer than 6 depending on the magnitude of man-made signals. Chapter 4 provides additional detail on the technique's capabilities and limitations.

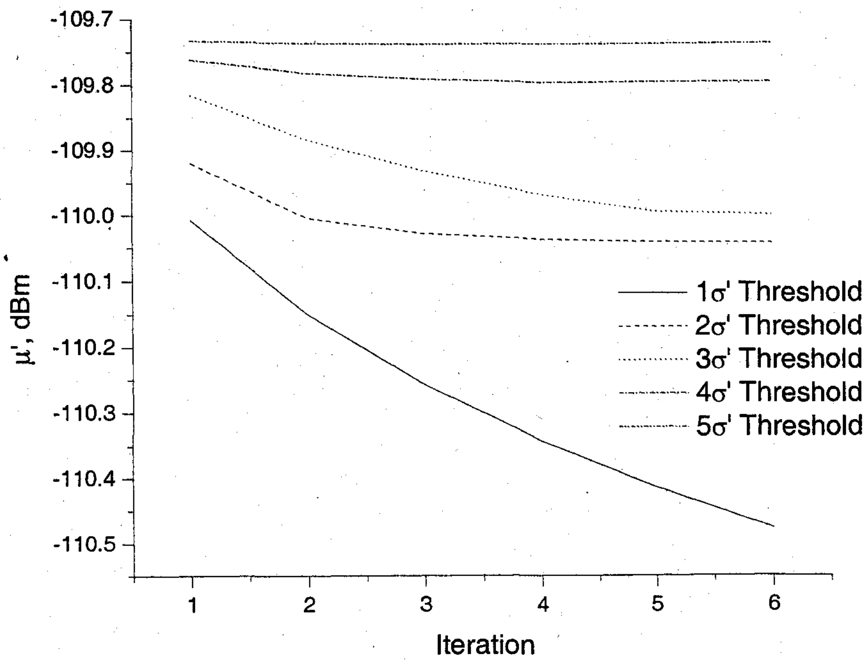

Figure 2.11. Ambient noise mean estimates after each iteration

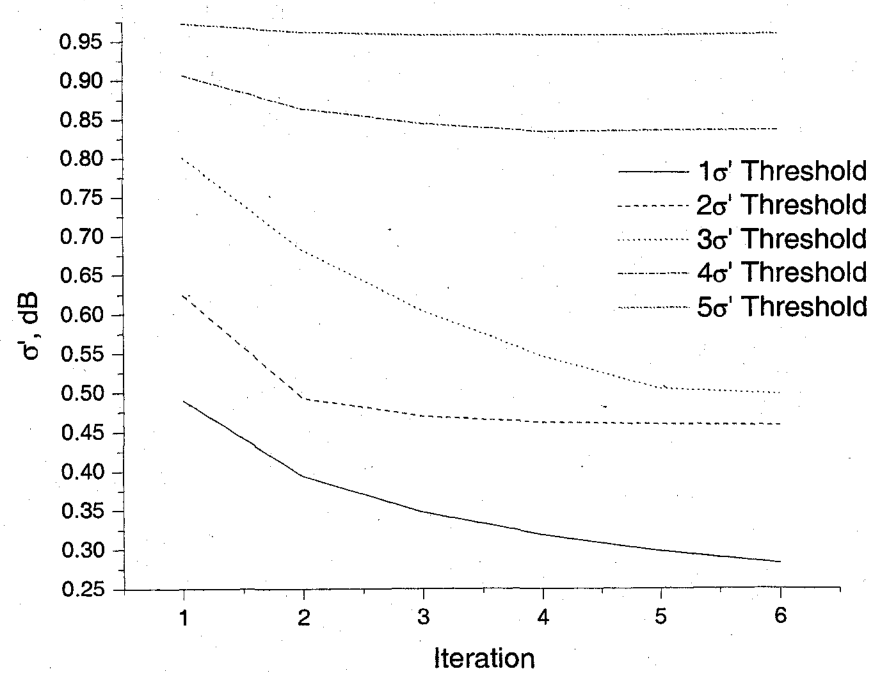

Figure 2.12. Ambient noise standard deviation estimates after each iteration

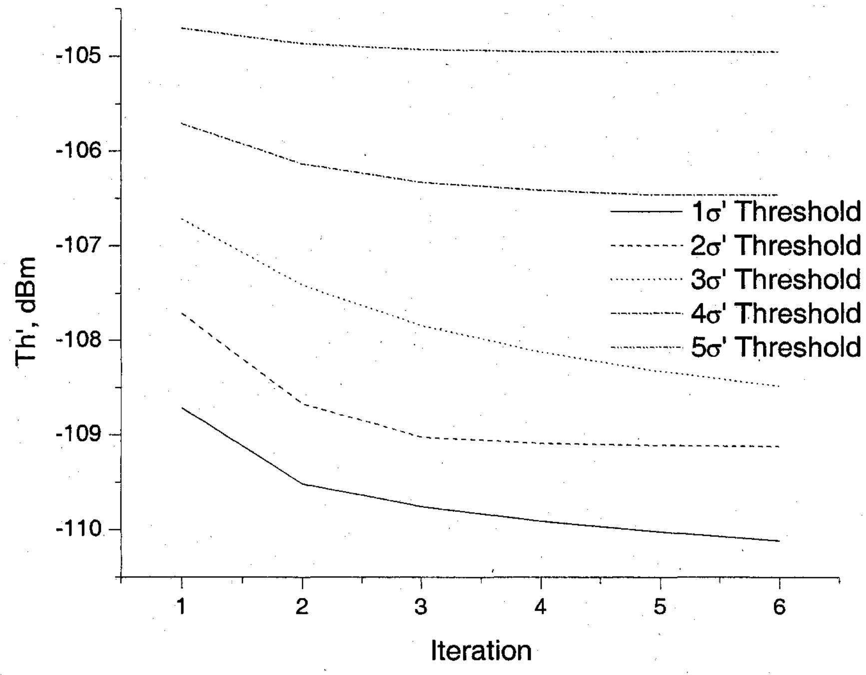

Figure 2.13. Ambient noise bypass threshold estimates

2.3. Decision Making Process Flow

Tables 2.3 and 2.4 show general EMI test flow using the technique described in the previous section to remove man-made signals from the EUT EMI spectrum.

The first section of the flow describes the process for detecting man-made signals in the environmental noise spectrum. Once the signals have been detected, their frequencies are added into the bypass list. At this stage in the process, parameters such as the measured noise mean, standard deviation and available bandwidth are monitored. This part of the flow is performed with the EUT turned off.

The second section of the flow describes actual EMI test when the EUT is turned on. The frequencies that are included in the bypass list are removed from the measured EMI spectrum. Parameters such as EMI mean and standard deviation are monitored. A circled number next to each block refers to more detailed description provided below.

Measured environmental spectrum statistical parameter (μ and σ) upper limits must be set in order to detect the overall upper limit on ambient noise. A high overall noise level may mask EMI components during the second phase of the testing when EUT is on. The parameter limits must be set to 1-3 dB above the receiver's thermal noise, which is measured with a termination on the antenna input. Establishing the parameter limits is part of the calibration procedure performed prior to EMI testing. If reasonable limits cannot be established due to a high average noise level, this will indicate that the location may not be suitable for measurements.

A detailed test flow that determines bypass frequencies and measures EUT EMI must be as described below.

Section	Sub-section	Operation
1	1	Turn off the EUT. Scan the frequency range from F_1 to F_N, where F_1 and F_N are start and stop frequencies respectively, and N is the number of data samples. Store the signal level reading in data vector **S**.
	2	Calculate signal level mean μ and standard deviation σ. Then calculate threshold Th using expression 2.3.
	3	If μ and σ are within the specified limits proceed to the next step. Otherwise stop the measurement and consider different time and/or location for the test.
	4	Generate or update (if this is not a first iteration) frequency bypass list: **for** $i = 1 \ldots N$ **if** $S_i >= Th$ **then** $L_{j++} = F_i$, where **L** is the bypass list data vector, and j is the bypass list index.
	5	Calculate the remaining available bandwidth after signal bypass: $Bw = 100*(N - M)/N$, where M is the number of the frequencies stored in **L**; **if** Bw >= 90% proceed to the next step, otherwise stop the measurement and consider different time and/or location for the test.
	6	Repeat steps 1.1 to 1.5 until the desired number of iterations is performed. A practical value of this parameter is shown in the following chapter section.

Table 2.3. Section 1 of the EMI test flow.

Section	Sub-section	Operation
2	1	Turn the EUT on. Scan the frequency range from F_1 to F_N. Store the signal level readings in the data vector **S**
	2	Remove all man-made signals from the recorded spectrum **for** $i = 1...N$, **if** $F_i \subset \mathbf{L}$ then remove S_i from **S** forming a new data vector **S'**
	3	Calculate mean μ, standard deviation σ, and maximum signal level of the vector **S'**
	4	Display and store the results.
	5	Repeat steps 2.1 to 2.4 if necessary.
	6	The results from step 2.4 can now be used as EMI characteristics of the EUT.

Table 2.4. Section 2 of the EMI test flow.

2.4. Results

Figure 2.14 shows a typical amplitude distribution of the ambient noise frequency spectrum (figure 2.15) that includes external radiation sources. The amount of man-made signal was less than

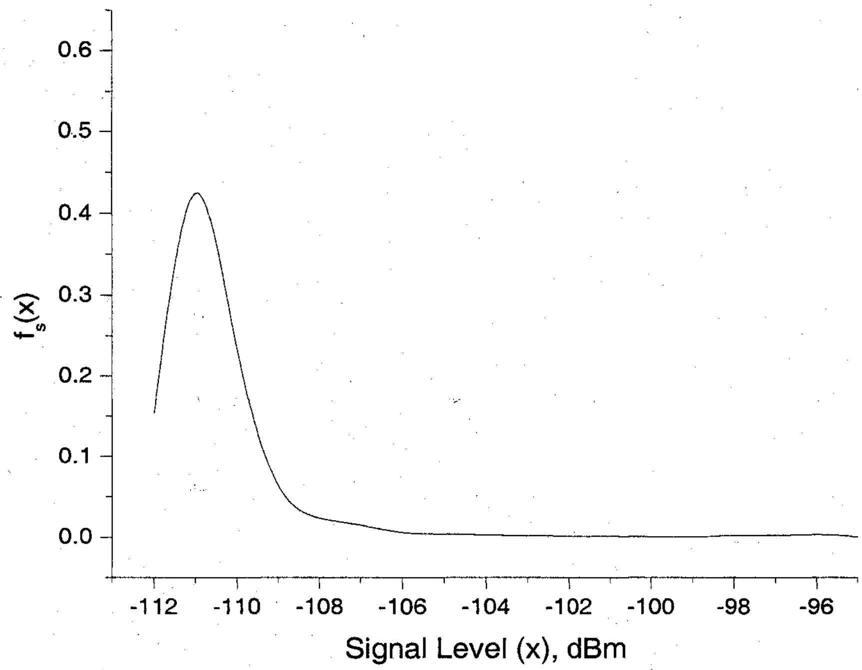

Figure 2.14. Typical measured ambient noise signal level distribution

10% of the overall bandwidth, and therefore the distribution of the man-made signal cannot be seen as clearly as in the model. For the distribution in figure 2.14, the estimate of the bypass threshold that removes man-made signals is around -108.5 dBm.

As is shown in figure 2.16, the typical man-made noise signal levels do not exceed -94 dBm and usually have bandwidth around 25 kHz.

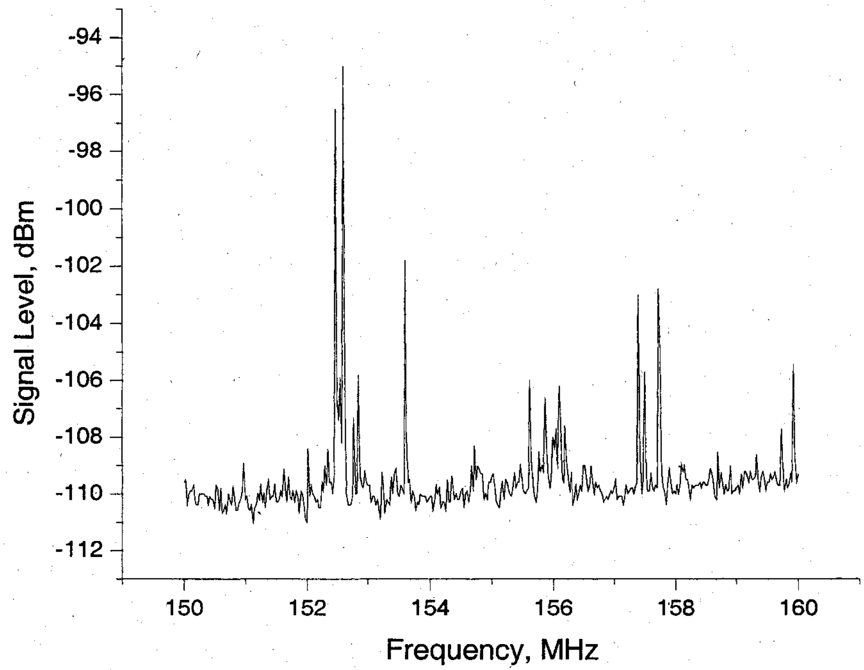

Figure 2.15. Typical measured spectrum of ambient noise including man-made signals

Figure 2.17 illustrates changes in threshold calculated with different σ coefficients as the number of iterations increases.

Threshold values typically descend quickly to a stable level during first three frequency sweeps. Thresholds with σ coefficients of 4 and 5 may deviate within 1 dB after the third sweep due to changes in the ambient noise mean level after each sweep. This also indicates that those thresholds were high enough to let some of the lower-level man-made signals to pass after high signals had been removed.

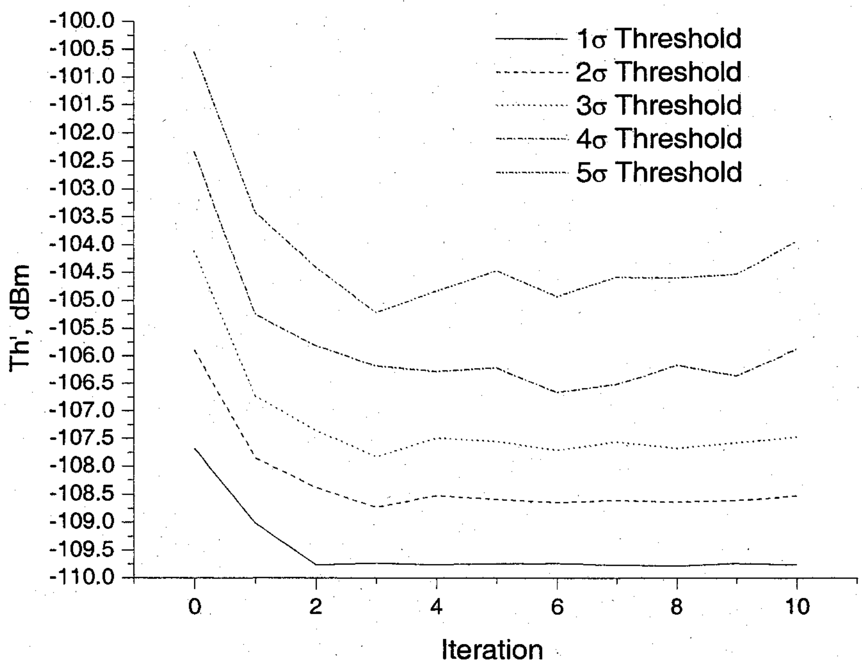

Figure 2.16. Calculated threshold values for different s after each iteration

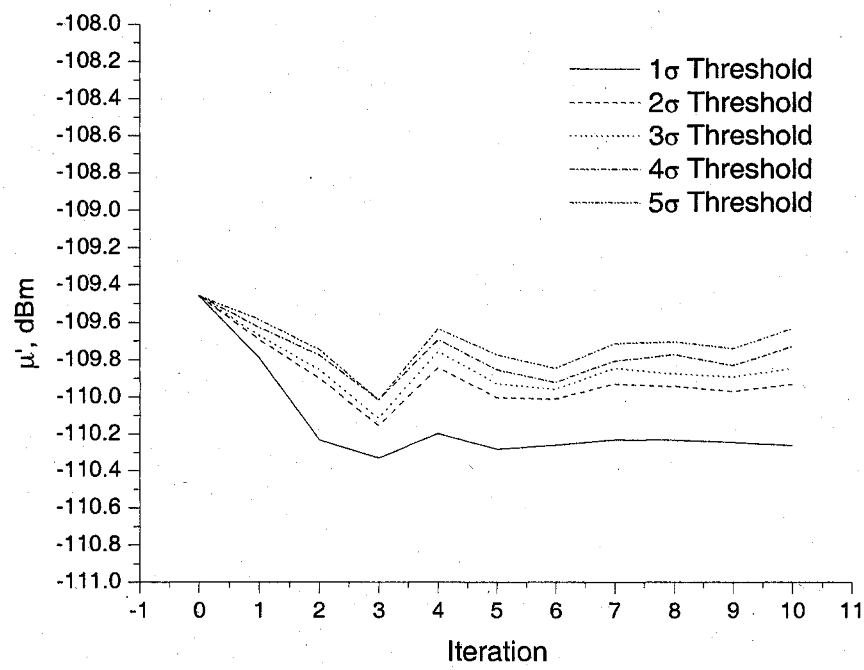

Figure 2.17. Measured ambient noise estimated mean values

Since the amount of man-made signals present in measured spectra is generally less than the 10% assumed in the model, the estimated mean values for different thresholds show less than 0.5 dB of the difference for up to three frequency sweeps (figure 2.18). In addition, the ambient noise mean estimate for 1σ threshold is lower by 0.3 dB, since such a low threshold removes a significant amount of the ambient noise and therefore brings the mean level closer to the ambient noise minimum signal level.

Estimated ambient noise standard deviation values for different thresholds (figure 2.19) typically approach their minimum levels after 3 to 4 sweeps. For 2 and 3σ thresholds, standard deviation curves show less than a 0.2 dB deviation from minimum value during next sweeps.

Table 2.3 summarizes the data used to plot charts in figures 2.17 – 2.20.

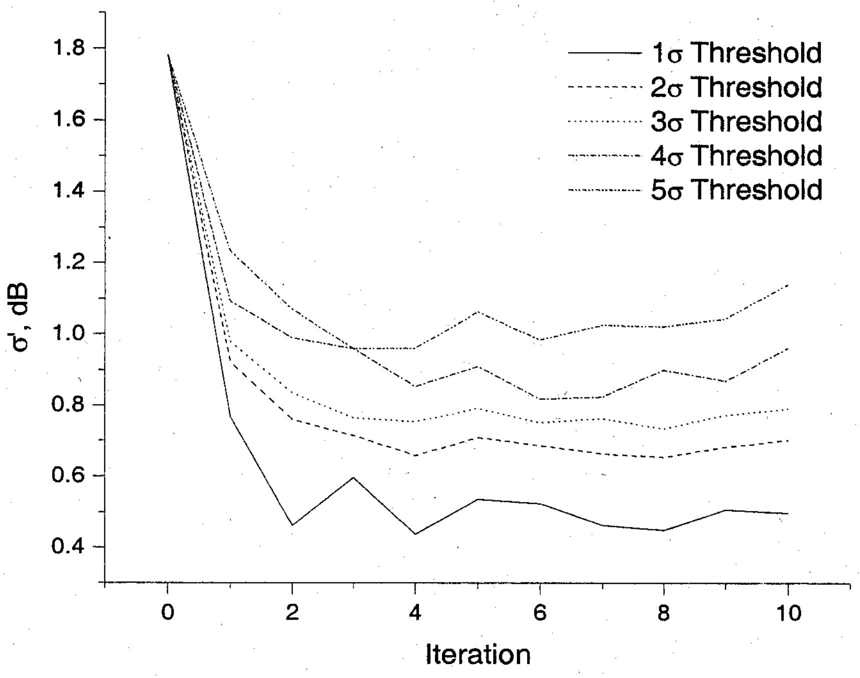

Figure 2.18. Measured ambient noise estimated standard deviation

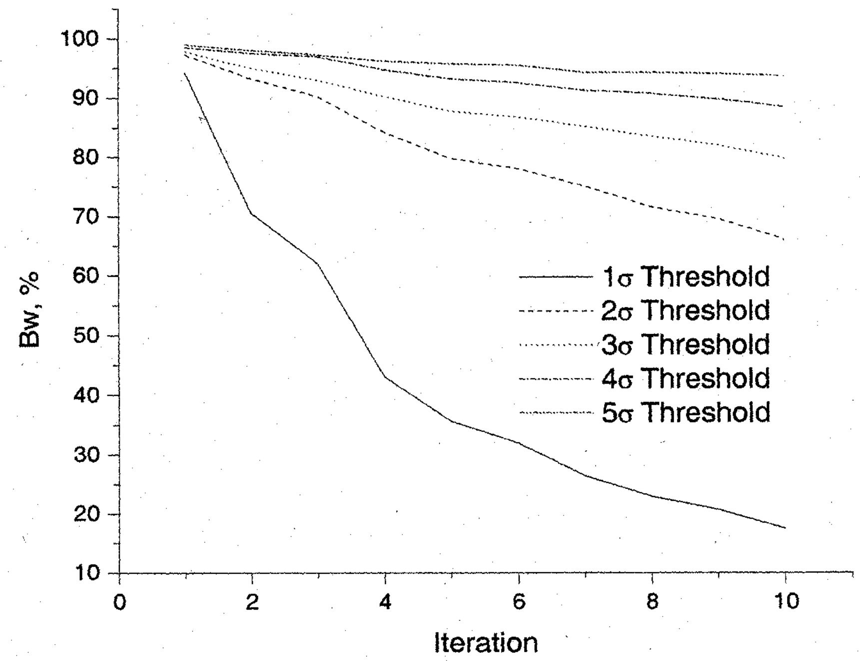

Figure 2.19. Remaining available bandwidth after man-made signal bypass

i	1σ Threshold				2σ Threshold				3σ Threshold				4σ Threshold				5σ Threshold			
	μ', dBm	σ', dB	Th', dBm	Bw, %	μ', dBm	σ', dB	Th', dBm	Bw, %	μ', dBm	σ', dB	Th', dBm	Bw, %	μ', dBm	σ', dB	Th', dBm	Bw, %	μ', dBm	σ', dB	Th', dBm	Bw, %
0	-109.46	1.78	-107.68	100	-109.46	1.78	-105.89	100	-109.46	1.78	-104.11	100	-109.46	1.78	-102.33	100	-109.46	1.78	-100.54	100
1	-109.79	0.77	-109.02	94.26	-109.69	0.92	-107.85	97.26	-109.67	0.98	-106.73	97.76	-109.63	1.09	-105.26	98.5	-109.59	1.23	-103.42	99
2	-110.23	0.46	-109.77	70.57	-109.9	0.76	-108.38	93.27	-109.85	0.84	-107.35	95.01	-109.78	0.99	-105.82	97.51	-109.75	1.07	-104.4	98
3	-110.33	0.6	-109.73	62.09	-110.16	0.71	-108.73	90.27	-110.12	0.76	-107.82	93.02	-110.02	0.96	-106.18	97.01	-110.02	0.96	-105.22	97.26
4	-110.2	0.44	-109.76	43.14	-109.84	0.66	-108.53	84.29	-109.76	0.75	-107.5	90.27	-109.69	0.85	-106.28	94.76	-109.64	0.96	-104.83	96.26
5	-110.28	0.54	-109.74	35.66	-110.01	0.71	-108.59	79.8	-109.93	0.79	-107.55	87.78	-109.86	0.91	-106.21	93.27	-109.77	1.06	-104.46	95.76
6	-110.26	0.52	-109.74	31.92	-110.01	0.69	-108.64	78.05	-109.96	0.75	-107.71	86.78	-109.92	0.82	-106.65	92.52	-109.85	0.98	-104.93	95.51
7	-110.23	0.46	-109.77	26.43	-109.93	0.66	-108.61	75.06	-109.85	0.76	-107.56	85.29	-109.81	0.82	-106.52	91.27	-109.71	1.03	-104.58	94.26
8	-110.23	0.45	-109.78	22.94	-109.94	0.65	-108.64	71.57	-109.88	0.73	-107.67	83.54	-109.77	0.9	-106.17	90.77	-109.7	1.02	-104.59	94.26
9	-110.24	0.51	-109.74	20.7	-109.97	0.68	-108.61	69.58	-109.89	0.77	-107.58	82.04	-109.83	0.87	-106.36	89.78	-109.74	1.04	-104.52	94.01
10	-110.26	0.5	-109.76	17.46	-109.93	0.7	-108.53	66.08	-109.85	0.79	-107.48	79.8	-109.73	0.96	-105.88	88.53	-109.63	1.14	-103.93	93.77

Table 2.5. Measured ambient noise estimated parameters summary

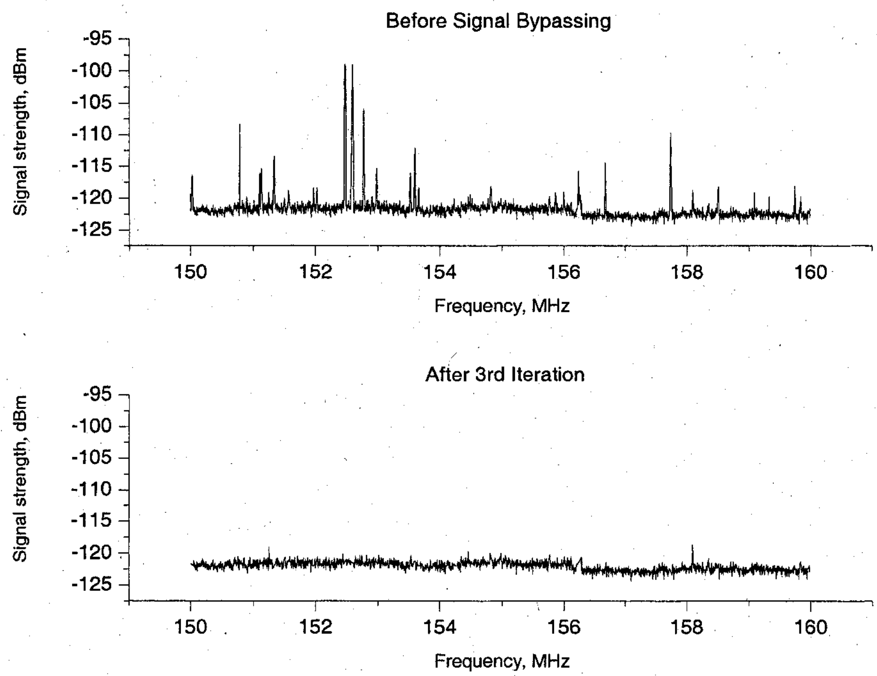

Figure 2.20. Ambient noise spectrum before and after signal bypass using 1σ threshold

Concluding this chapter, Figures 2.21 to 2.25 demonstrate the effect of the different thresholds on the ambient noise spectrum after three frequency sweeps.

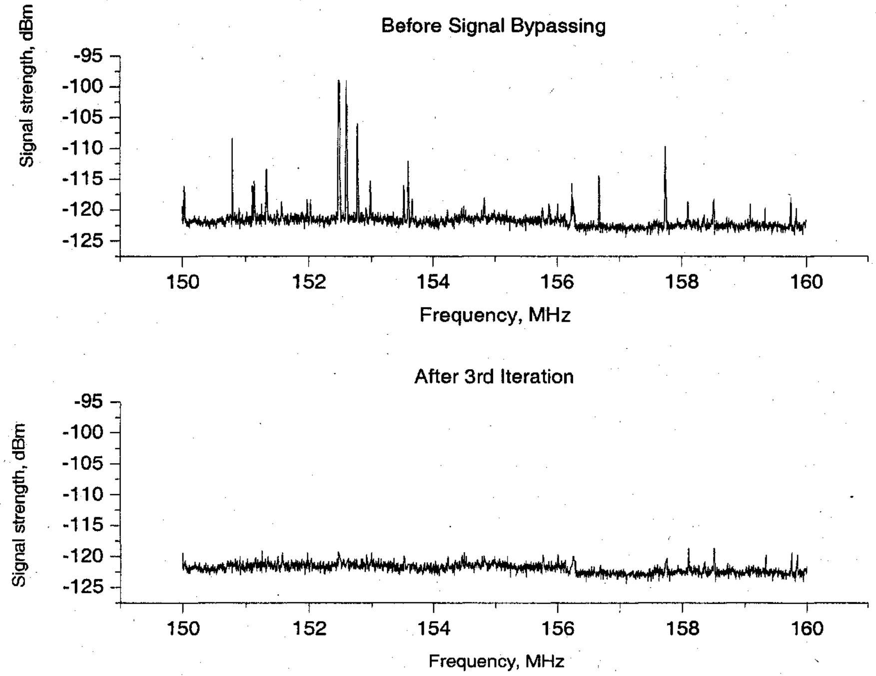

Figure 2.21. Ambient noise spectrum before and after signal bypass using 2σ threshold

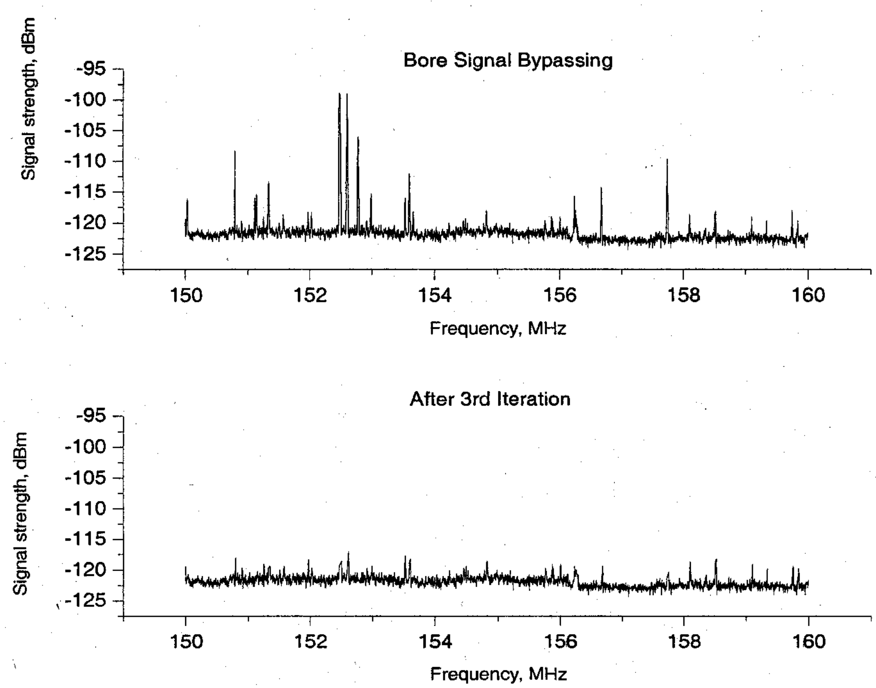

Figure 2.22. Ambient noise spectrum before and after signal bypass using 3σ threshold

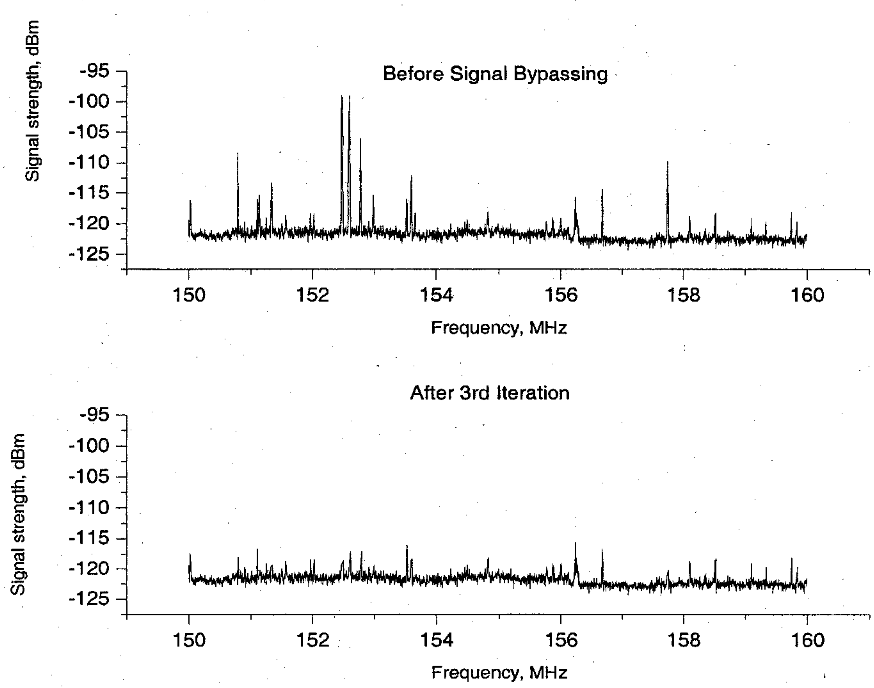

Figure 2.23. Ambient noise spectrum before and after signal bypass using 4σ threshold

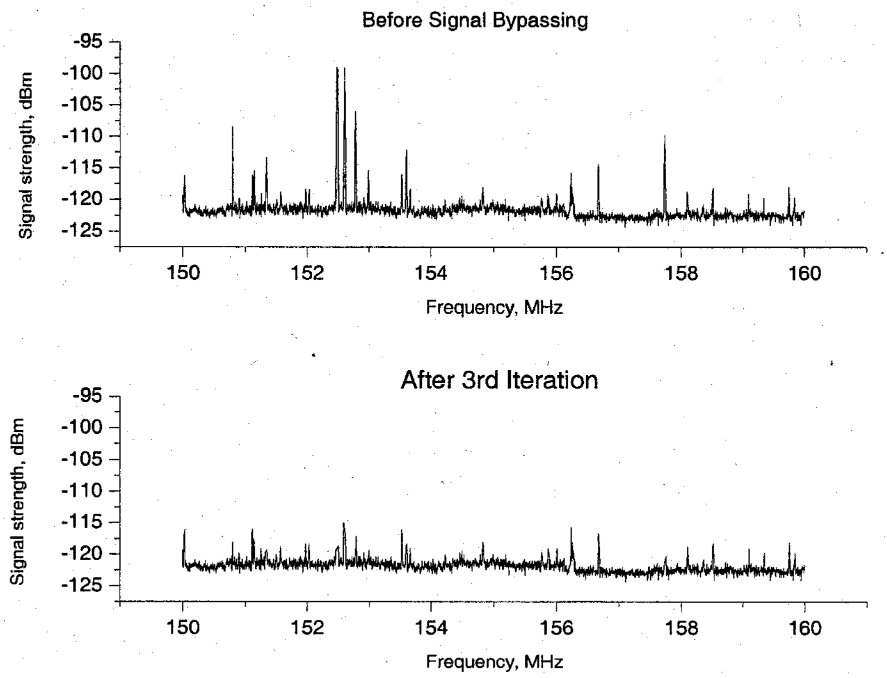

Figure 2.24. Ambient noise spectrum before and after signal bypass using 5σ threshold

2.5. Conclusion

This chapter addresses the statistics of environmental noise spectra containing both signals and noise, in addition to those containing noise alone. A computer simulation shows the effects of applying different bypass thresholds to identify man-made signals. That model shows that for an ambient noise spectrum with Gaussian amplitude distribution, a 3σ threshold gives best estimates of the noise parameters and removes 100% of the man-made noise. The model also shows that using a 3σ threshold requires six frequency spectrum measurements (sweeps) in order to obtain close to the ambient noise parameter estimates.

The bypass process that uses spectral statistics is described in section 2.3 of this chapter. The process flow diagram shows key operations and essential parameters that are to be performed during the measurement. The program flow can be directly implemented in an automated EMI measurement system. An example of such system software and hardware is shown in the following chapter. The trade-offs between accuracy, bandwidth and convergence time are described in chapter 5.

Chapter 3 concludes with the results of a bypass process on real spectra obtained from a range of electromagnetic environments. Although the deterministic model presented in this chapter suggests the use of a 3σ threshold, work with measured spectra show that a 2σ threshold provides the best results for practical applications. The difference between ambient noise estimated parameters for 2 and 3σ thresholds does not exceed 0.2 dB, although the 2σ tends to converge more quickly (four iterations rather than six iterations).

CHAPTER 3

HARDWARE AND SOFTWARE USED FOR CONCEPT VALIDATION

The main hardware component of the EMI testing system is the computer-controlled WiNRAiIO receiver [6]. This is a general-purpose, high-end external receiver intended for government, military, security, surveillance, media monitoring and industrial applications. The frequency range is 150 kHz to 1.5 GHz. The external unit connects to an IBM PC compatible computer via a serial interface cable. The WiNRADiO WR-3150e hardware/software package consists of the receiver unit, Windows-based software, RS-232 cable, multi-voltage power adapter, start-up antenna and a user's manual.

At the rear of the unit, there are connectors for the antenna, serial control port, PCMCIA control port, external speaker, power and a data output interface (figure 3.2).

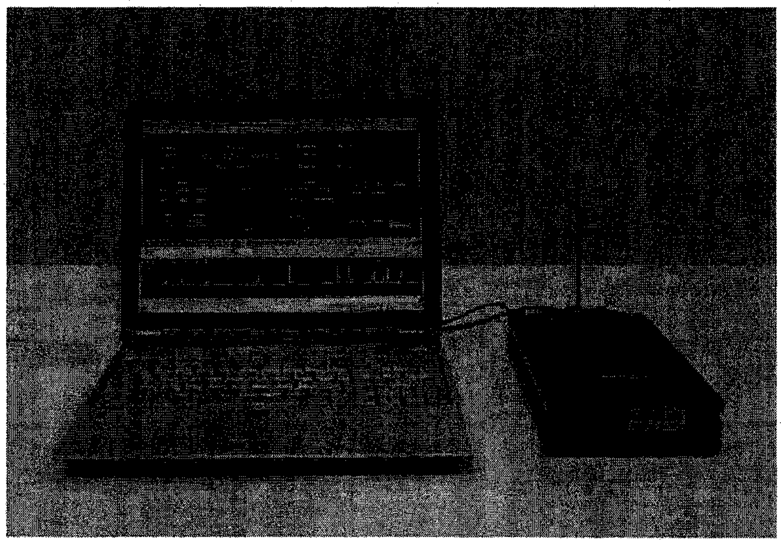

Figure 3.1. Receiver connected to laptop PC

The PPS (Portable Power Source) is an add-on option for external models of the receiver, to provide mains-independent power for field operations. The PPS is designed to mount directly underneath the receiver.

The PPS is used as the primary power source when the measurements are preformed. The use of the power adapter is not recommended due to its high radiated EM noise that can interfere with measurements.

Figure 3.2. Back panel of the receiver with the Portable Power Source connected

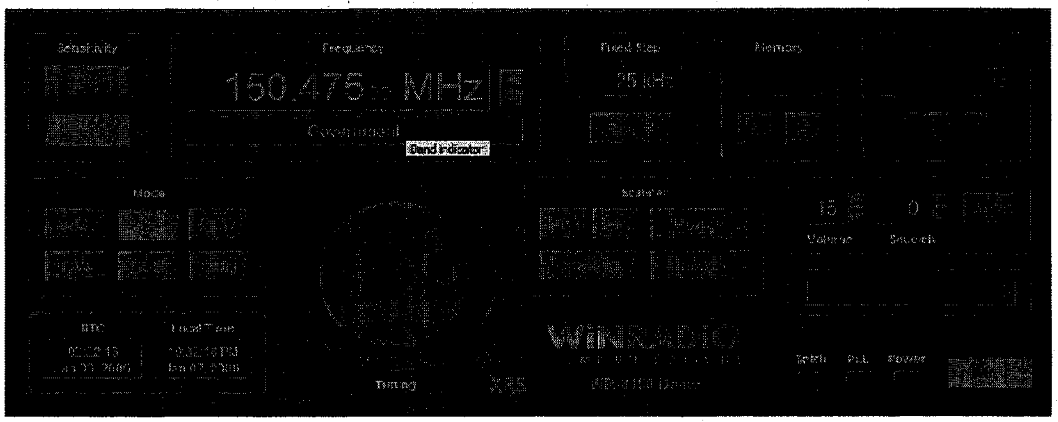

Figure 3.3. Standard application console

The receiver is used with standard monopole roof-mount antenna designed for a specific frequency range. The antenna can be connected via 50Ω coaxial cable with a BNC connector.

The receiver is supplied with Windows-based software which provides tuning and scanning options. Support is also provided for software developers wishing to write their own applications code for the receiver.

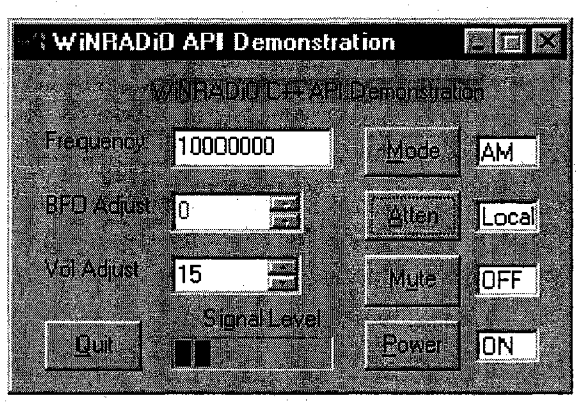

Figure 3.4. An example of the radio API interface in C/C++

The API is implemented in both 16 and 32 bit drivers: WRAPI.DLL for 16 bit applications (Windows 3.1x and 95) and WRAPI32.DLL for 32 bit applications(Windows 95, 98, NT 3.5 & 4, 2000 and XP).

Despite the fact that the present receiver cannot show the performance usually expected from the specialized EMI/EMC tools, it can be used as an inexpensive substitute in cases when mobility and affordable price are priorities. The programming options make it a versatile tool not only for EMI but for many other radio related applications.

The EMI testing software is a software implementation of the EMI analysis procedure described in the previous chapters. Its main goal is to automate the process of gathering and analyzing the EMI generated by the EUT. It has been designed specifically for the WiNRADiO family receivers and utilizes the SDK provided by the receiver's manufacturer, although all of the concepts presented here can be readily applied to other computer-controlled receivers. The Appendix B consists of programming information for WiNRADiO receivers.

The majority of the data analysis was performed using Matlab. The Matlab routines (see Appendix C) were using the data collected by a simplified version of EMI Testing Software. The Matlab routine algorithms were then implemented in the EMI testing software.

CHAPTER 4

PRACTICAL CONSIDERATIONS: ACCURACY, REPEATABILITY, MEASUREMENT TIME, TECHNIQUE LIMITATIONS

When using the technique described here, large spectral components of EMI might exist at frequencies bypassed in the measurement process. When bypassing external radiation frequencies in the background noise spectrum, the same frequencies will be avoided in the EUT EMI spectrum. This will cause the reported EMI averaged over the frequency range to be less than the actual EMI, although this is not considered to be detrimental to the process for reasons that are described below.

EMI spectra for all in-vehicle electronic devices investigated in this study tend to be distributed throughout the frequency range, similar to what is shown in the Figure 4.1.

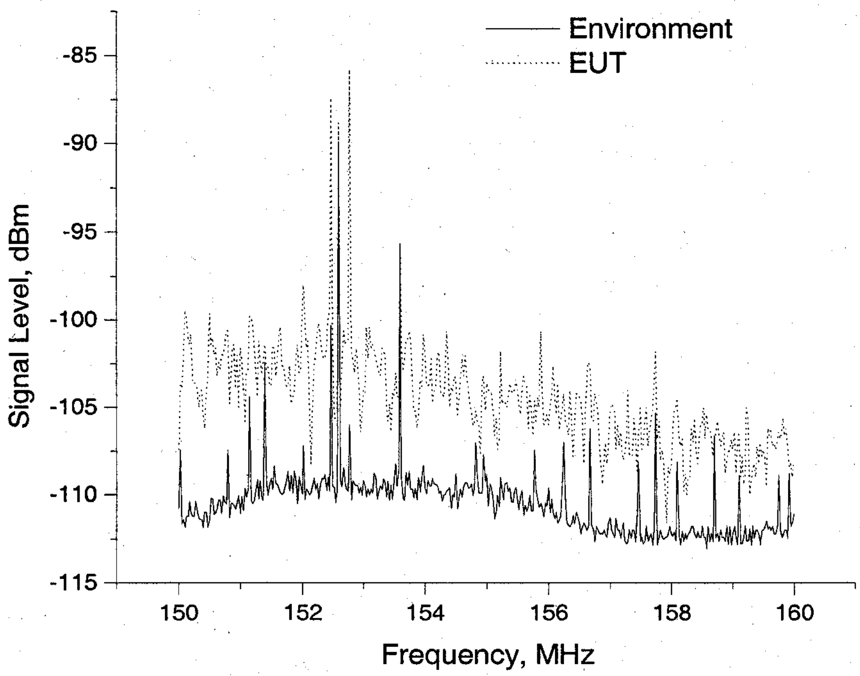

Figure 4.1. EUT EMI and ambient noise spectra

The computer model in chapter 2 simulated environmental noise with 10% of man-made noise contamination. When dealing with noise with much higher amounts of man-made noise, the processing of such noise will require a greater number of iterations. The environmental noise mean will grow as the amount of man-made noise increases and therefore will push the threshold higher. Consequently, that higher threshold will remove a lesser amount of man-made noise which will necessitate a greater number of iteration steps. Thus, although the technique is capable of dealing with noise spectra with high amounts of man-made noise, the most efficient operation will be achieved with spectra that have less than 10% man-made noise contamination.

As would be expected, the technique works best in a stable electromagnetic environment. In such an environment, the amount and frequencies of the man-made signals do not change or change rarely. If at each frequency scan new man-made signals appear in the spectrum, they will be removed with the current threshold which will decrease the overall remaining bandwidth.

When using bypass threshold it must remove less than 10% of the scanned frequency range. Otherwise, the electromagnetic environment is considered to be too noisy and the measurements cannot be performed accurately since measured EMI can be polluted with external signals that may appear during the test. The errors resulting from the elimination of less than 10% of the frequency range are considered to be negligible for this application.

For the noise spectra with less than 10% man-made signals, creating a bypass list takes 3 to 4 frequency range sweeps. After that, estimated ambient noise parameters (mean and standard deviation) of the consequent sweeps will lie within less than 0.5 dB of the estimated value as shown in the figures 2.17 and 2.18.

When measured at different locations ambient noise and external radiation sources can vary considerably. Figure 4.2 shows average background noise levels measured at different times, dates and locations. Two lines on the top of the graph represent an environment with relatively high average background noise level. Although the amount of external radiation sources in those environments does not exceed 10% (figure 4.4), measurements in such environments must not be done.

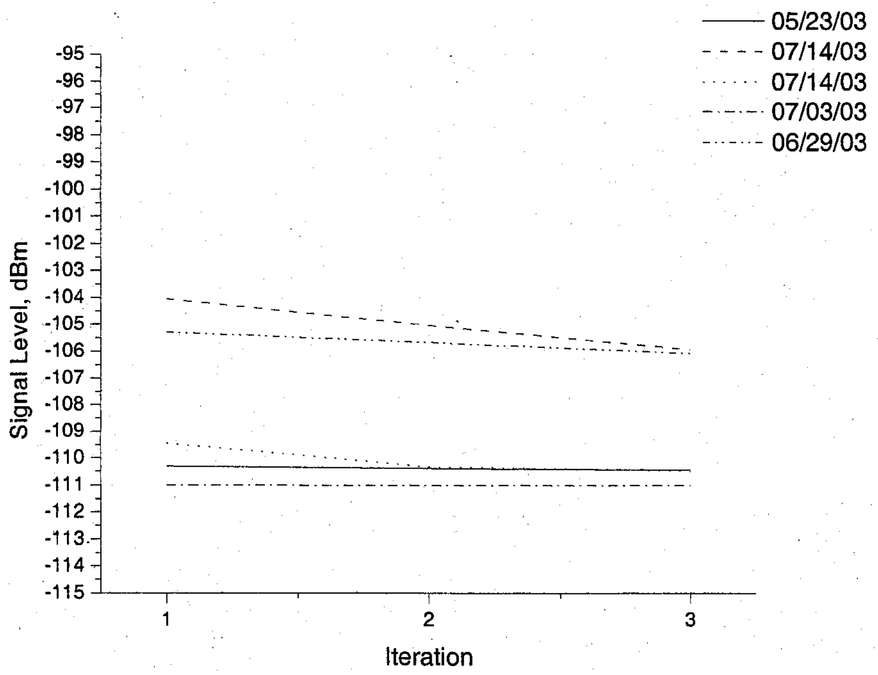

Figure 4.2. Average noise level after signal bypass for different dates and locations

As evident in the figures, the bottom plots agree to within 2 dB. The average levels comply with the average background noise levels measured in [3].

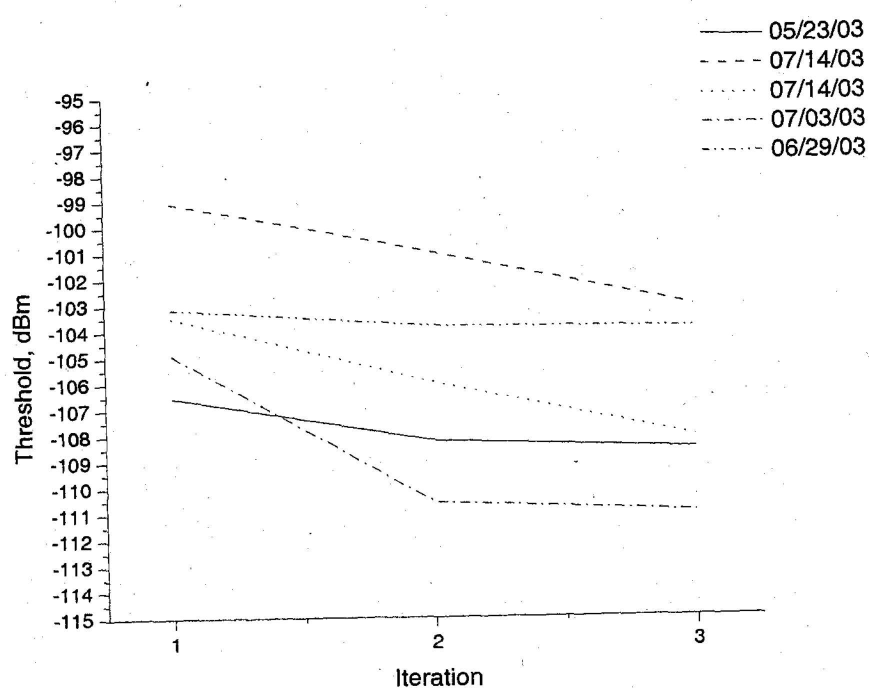

Figure 4.3. Signal bypass thresholds for different dates and locations

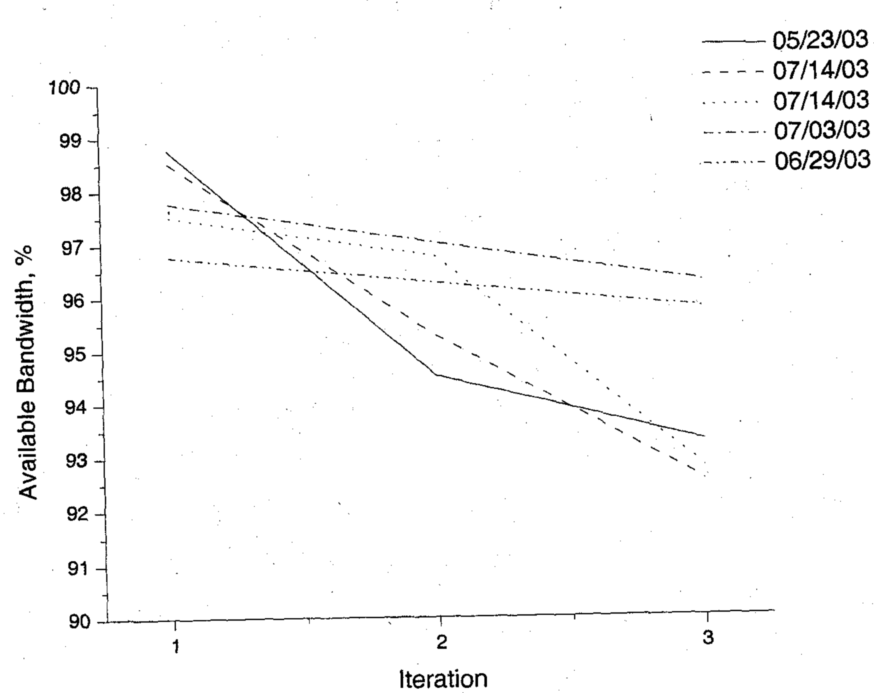

Figure 4.4. Available bandwidths after signal bypass for different dates and locations

Device	EMI Level, dBm		Difference, dB
	Location #1	Location #2	
Computer and Monitor	-110.23	-111.26	1.03
Radio Control Head	-116.81	-114.94	-1.87
Light bar	-109.65	-111.38	1.73
Entire System	-111.65	-112.07	0.42
Entire System w. Engine Running	-110.08	-112.44	2.36

Table 4.1. EMI measurements repeatability

Measurements of EMI on the same vehicle in significantly different electromagnetic environments provided very similar results. The repeatability of average EMI measurements using this technique was within 3 dB (see Table 4.1).

Table 4.1 shows a comparison of the average EMI levels measured at two different locations. The Device column indicates the EUT that was used as EMI radiation source. Each device was turned on separately, and then the background noise and EMI measurements were taken.

The time required to perform an EMI evaluation depends on several test parameters: the frequency range being scanned, the frequency resolution and the number of environmental noise and EMI spectra scans. The testing time mostly depends on how fast the hardware can tune from one frequency to another and perform a measurement. Also, the software needs time to receive data, process them and store them.

Most of the contemporary digital receivers and signal analyzers are capable of switching from channel to channel in under 20 ms. Given that, and a frequency range of 10 MHz, scanning with the step of 25 kHz will result in a sweep time of about 8 seconds.

In general, performing a single EMI evaluation entails three ambient noise sweeps needed to create a bypass list, and two or three sweeps to measure the EUT's EMI radiation. Therefore, the overall test time, including the hardware sweep time and all the computations, is roughly 2 minutes per EUT. However, in areas or frequency bands where signal transmissions are not intermittent, the test times tend to be significantly less than specified above.

This technique can be implemented virtually on any type of signal level measuring hardware capable of being operated by a computer. The measuring hardware must be able to send digitized signal level data to the computer for processing. Also, the hardware must be capable of varying measurement parameters such as frequency resolution, bandwidth, measurement accuracy and measurement time. The limitations for applying this technique mostly depend upon measuring system hardware and software used to implement it.

The technique can also be used on systems that radiate EMI in a relatively wide band. During the noise processing, some of the spectral components will be bypassed, which may cause an error in EMI measurement if the narrow-band frequency components are located in the bypassed frequencies. However, for spectra containing less than 10% man-made signals, such error will be negligible, as the narrow-band EMI components will add very little to measured ambient noise level.

CHAPTER 5

CONCLUSIONS

The result of this work is a technique for measuring in-vehicle electronic equipment EMI without requiring the measurements to be made inside a shielded anechoic chamber. The primary contribution of this work is the development of a method for measuring EMI when external radiation is present. The technique uses received spectral analysis to assess the presence of interfering signals, and it is able to accomplish this task using relatively low-cost, off-the-shelf equipment.

While the approach was developed for a particular frequency band (viz., the VHF emergency band), the results can be readily applied to other frequency ranges. All necessary information for translating this approach to another frequency band is described, and inherent tradeoffs between measurement accuracy and the time it takes to perform an assessment have been quantified.

Although this paper presents a completed technique some further research can be done in order to improve speed and quality. A frequency spectrum of interest can be broken into a number of smaller ranges that are analyzed separately. This will help to minimize ambient noise errors due to variability of the ambient noise floor along the frequency range. Using FCC data base in conjunction with signal bypass can help to speed up the measurements. Finally, an EMI testing system based on this technique can be implemented as an embedded system for continuous EMI monitoring.

The paper describing the concepts of the work presented here achieved an excellent award in 2004 International Symposium on Electromagnetic Compatibility in Sendai, Japan (Appendix D).

REFERENCES

[1] The web site for Project 54 is: http://www.project54.unh.edu/about/

[2] Man-Made Noise Power Measurements at VHF and UHF Frequencies, Robert Achaz and Roger Dalke, National Telecommunications and Information Administration, U.S. Dept. of Commerce, NTIA Report 02-390, December, 2001.

[3] Man-Made Noise in the 136-138 MHz. VHF Meteorological Satellite Band, Achatz, Lo, Papazian, Dalke, and Hufford, National Telecommunications and Information Administration, U.S. Dept. of Commerce, NTIA Report 98-355, September, 1998

[4] Information about the FCC Frequency Assignment Database is given at: http://www.fcc.gov/oet/info/database/

[5] Vaseghi, Saeed V., Advanced Digital Signal Processing and Noise Reduction, Second Edition, Wiley, New York, 2000

[6] Kent Chamberlin, Maxim Khankin, Measuring the Impact of In-vehicle-generated EMI on VHF Radio Reception in an Unshielded Environment, 2004 International Symposium on Electromagnetic Compatibility, Sendai, 2004

APPENDICES

APPENDIX A

Ambient Noise Computer Simulation Matlab Routine.

```
close all;
clear all;

mn=-110; sn=0.5; %mean and deviation of the ambient noise
mm=-98; sm=3;    %mean and deviation of the man-made signal
avbw=0.1;        %amount of the man-made signals
                 %relative to original bandwidth - 0..1
L = 500000;      %number of signal samples
ns=3;            %threshold n*sigma parameter

nsig = randn(L,1)*sn+mn; sig=nsig;        %ambient and mixed signal
vectors

mmsig = lognorm(-104, -108.5, 0, 0.8, L);  %man-made signal vector

ind=randperm(L);         %random permutations of ambient noise vector
indices
ind=ind(1:L*avbw);       %take L*avbw random samples from sig
sig(ind)=mmsig(ind);     %and replace them with man-made signal samples

sgmin = min(sig); sgmax = max(sig);       %min and max distribution x-
axis values
step = 0.0916;                            %distribution x step
xs = sgmin:step:sgmax;                    %distribution x-axis values
vector
ndist = hist(sig,length(xs))/length(sig); %mixed signal amplitude
distribution

sgmin = min(mmsig); sgmax = max(mmsig);                %distribution
x step
xm = sgmin:step:sgmax;                                 %distribution
x-axis
                                                       %values vector
mmdist = hist(mmsig(ind),length(xm))/length(mmsig(ind)); %man-made
signal amplitude
                                                       %distribution

%remove ma-made signal samples from ambient noise
nsig(ind)=0;
nind = find(nsig ~= 0);
```

```
nsig = nsig(nind);

sgmin = min(nsig); sgmax = max(nsig);        %distribution x step
xn = sgmin:step:sgmax;                       %distribution x-axis
                                             %values vector
sndist = hist(nsig,length(xn))/length(nsig); %ambient signal amplitude
                                             %distribution

nsigmean = mean(sig); sd=std(sig); %mixed signal statistical parameters
nsth = nsigmean+ns*sd;             %ambient signal based parameter
threshold

thind = find(sig<=nsth);   %find all indices where signal is below the
threshold
thsig = sig(thind);        %signal vector with the man-made signals
removed

%amount of the removed man-made signals
mmnsrmvd = 1 - ((L*avbw)-(length(sig)-length(thsig)))/(L*avbw);

sgmin = min(thsig); sgmax = max(thsig);       %distribution x step
xt = sgmin:step:sgmax;                        %distribution x-axis
values vector
thdist = hist(thsig,length(xt))/length(thsig);%processed signal
amplitude
                                              %distribution

%generate mixed signal mean and threshold
%marker line vectors
i = find(xs>=mean(sig));
mmse(1:length(xs))=0; mmse(i)=max(ndist);
i = find(xs>=nsth);
th(1:length(xs))=0; th(i)=max(ndist);


figure(1);
plot(xs, ndist);          %plot mixed signal distribution
hold on;
plot(xn, sndist,'--r'); %plot ambient signal distribution
plot(xm, mmdist,'-.g'); %plot man-made signal distribution
plot(xt, thdist,':y');  %plot signal distribution after applying
threshold
plot(xs, mmse,'r');       %plot signal average value marker
plot(xs, th,'m');         %plot signal threshold marker

%format the data to be saved
sdata=[xs' ndist'];
ndata=[xn' sndist'];
mdata=[xm' mmdist'];
thdata=[xt' thdist'];

%display signal statistics
disp('******************************');
```

```
ns                          %sigma coefficient
smu = mean(sig)             %mixed signal mean
ssigma = std(sig)           %mixed signal standard deviation
sfmax = max(ndist)          %mixed signal distribution max value
thmu = mean(thsig)          %processed signal mean
thsigma = std(thsig)        %processed signal standard deviation
thfmax = max(thdist)        %processed signal distribution max value
mmnsrmvd = 100*mmnsrmvd     %amount of man-made signals removed
nsth                        %calculated threshold

%save the data
save thnoise.dat thdata -ascii
save mixnoise.dat sdata -ascii
save mmnoise.dat mdata -ascii
save ambnoise.dat ndata -ascii
```

APPENDIX B

Programming Information for WiNRADiO 1000/1500/3000 Series Receivers.

This document outlines API specification for the WR-1000, WR-1500 and WR-3000 series receivers, both internal and external. The API in implemented in both 16 and 32 bit drivers: WRAPI.DLL for 16 bit applications (Windows 3.1x and 95) and WRAPI32.DLL for 32 bit applications (Windows 95, 98, NT 3.5x & 4.0, 2000 and XP). A separate 16 bit DLL is provided for Windows NT that trunks to the 32 bit DLL.

Each function shows its declaration in C and in Delphi (Pascal) and can be used in both 16 and 32 bit environments without modification. The only difference is that 32 bit applications have to use WRAPI32 while 16 bit applications have to use WRAPI.

It is strongly recommended to use exception handling to close the radio device if an exception occurs while a radio device is open (the examples at the end do not use exception handling).

WRAPI SDK Functions:

OpenRadioDevice
CloseRadioDevice
GetRadioDeviceInfo
GetSignalStrength
GetRawSignalStrength

SetFrequency
SetMode
SetVolume
SetAtten
SetMute
SetPower
SetScanMode
SetBFOOffset
SetIFShift
SetAudioSource
SetDSPSource
SetAGC
SetIFGain

GetFrequency
GetMode
GetVolume
GetAtten
GetMute
GetPower
GetScanMode
GetBFOOffset
GetIFShift
GetAudioSource
GetDSPSource
GetAGC
GetIFGain

dspOpen
dspClose
dspSendByte
dspReadByte
dspOutWrite
dspInAddBuffer
dspBufferDone
dspPause
dspResume
dspInReset
dspOutReset
dspInOpen
dspOutOpen
DSP notifications

GetModeString
EnableRadioNotification

EnableAsyncMode
OpenRadioCount
GetDACValue
GetInterruptCount
GetDmaStatus
GetRadioInfoModeList
Is16bitRadio
LoadCalibrationData

Structures:

RADIOINFO
DSPHDR
ADUINFO
ADUANTENNAINFO

APPENDIX C

Measured Ambient Noise Matlab Processing Routines.

```
file: fsproc.m
%function reads and processes frequency sweep files in the specified
%folder
%the folder must contain only sweep data files
%first threshold is calculated based on the first sweep average signal
%level
%and standard deviation
%function plots average noise levels before and after signal bypass,
%thresholds and available bandwidth

close all;
clear all;

%read ambient noise data file
%get file name and path
[fname,pname] = uigetfile('\P54Test\Data\*.*','Browse for files');

files = dir(pname);  %get directory file list
type='Fsweep';       %set file data type
disp('Reading data...');
nf = length(files)-2;

nf=10;               %set number of files in the directory to read
                     %this variable must be commented out in order to
fres = 5;            %set frequency resolution

%read data files one by one
%each file represents one frequency sweep
for i=1:nf
    fname = sprintf('Sweep_%d', i)
    fname = sprintf('%s%s',pname,fname); %generate file name including
    sdata=getdata(fname,type);           %read data from the file (see
    N=length(sdata.slevel);              %get length of the data array
    sl(i,1:N)=sdata.slevel(1:N);         %extract signal level data
    t_dbm = t_wr2dbm(sdata.slevel);      %convert signal level data
    dbm(i,1:N) = t_dbm(1:N);
```

```
  f=sdata.frequency;                        %extract frequency data
end;
disp('...done');

close all;
disp('Processing data...');
threshold(1) = mean(dbm(1,:)) + 2*std(dbm(1,:)) %calculate first

for j=2:nf+1
   tdbm = dbm(j-1,1:fres:N); %temp signal level array, current sweep
   avgnl(j-1) = mean(tdbm); %average noise level of the original sweep
   sigma(j-1) = std(tdbm);                  %std of the original sweep
   abovethind = find(tdbm>threshold(j-1)); %indices of the noise sample
                                             %is above the threshold
   belowthind = find(tdbm<threshold(j-1));
   if j>2
      for i=1:length(abovethind)
         ind = find(exthind==abovethind(i));

         if length(ind)==0
            exthind = [exthind abovethind(i)];
         end;
      end;
   else
      exthind = abovethind;
   end;

   exthind = sort(exthind);   %array of indices that must be
                              %excluded from the original data
   tdbm2 = tdbm;
   tdbm(exthind) = 0;
   thind = find(tdbm);

   if length(thind)>0               %if new external signals are detected
      thdbm = tdbm(thind);          %array of processed signal
      thavgnl(j-1) = mean(thdbm); %avg noise level of the processed
      thsigma(j-1) = std(thdbm);   %std of the processed signal;
      threshold(j) = thavgnl(j-1) + 2*thsigma(j-1); %calculate next
      avlbw(j-1) = 100*length(thdbm)/length(tdbm);  %calculate
      j
   else                       %if no new external signals are detected
      thavgnl(j-1) = mean(tdbm2);     %avg noise level of the processed
      thsigma(j-1) = std(tdbm2);      %std of the processed signal;
      threshold(j) = threshold(j-1); %calculate next threshold
      avlbw(j-1) = avlbw(j-2);        %calculate available bandwidth

   end;


end;

nlmin = min(dbm); nlmax = max(dbm); %noise level min and max of all
avgnlmin = min(avgnl); avgnlmax = max(avgnl); % average noise level min
                                               %and max
fmin = min(f); fmax = max(dbm);                %start and stop sweep
                                               %frequencies
```

```
figure(1);
plot(avgnl);
title('Average Noise Level Before Signal Bypass');
xlabel('Data Sample Number');
ylabel('Signal Level, dBm');

figure(2);
plot(thavgnl);
title('Average Noise Level After Signal Bypass');
xlabel('Data Sample Number');
ylabel('Signal Level, dBm');

figure(3);
plot(threshold);
title('Signal Bypass Threshold');
xlabel('Sweep Number');
Ylabel('Threshold, bBm');

figure(4);
plot(avlbw);
title('Available Bansdwidth');
xlabel('Sweep Number');
ylabel('%');


%function getdata()
%this function reads a data file and puts the data into
%out structure where each data field has its own array
%the function is capable of reading three types of data files
%the data file type must be set as the function argument
%and must be on of the two: 'Snapshot' or 'Fsweep'
%the fname argument must include full file path

function out = getdata(fname,type)

switch type

%read the Snapshot type datafile
case 'Snapshot'
    fid = fopen(fname);              %open data file
 out.header = fscanf(fid,'%s',1);%read file header sectin of the data
                                 %file
    comment=' ';
    i=1;
    %read the comment section of the file
    while comment~='@'
        comment(i) = fscanf(fid,'%c',1);
        i=i+1;
    end;
    out.comment=comment;
    data = fscanf(fid,'%d,%d,%d',[3,inf]);   %read the signal
                                             %level data
    out.slength = length(data);              %record data array length
    out.sec(1:out.slength) = data(1,1:out.slength);    %extract data
                                                        %field values
    out.slevel(1:out.slength) = data(2,1:out.slength);%into specified
```

```
                                                                  %arrays
    out.dbm(1:out.slength) = data(3,1:out.slength);
    fclose(fid);  %close file

%read the Fsweep type data file
case 'Fsweep'
    fid = fopen(fname);%open datafile
    out.header = fscanf(fid,'%s',1);%read the header section of the
                                    %file
    comment=' ';
    i=1;
    %read the comment section of the file
    while comment~='@'
        comment(i) = fscanf(fid,'%c',1);
        i=i+1;
    end;
    out.comment=comment;
    data = fscanf(fid,'%d,%d,%f',[3,inf]);%read signal data into 2D
                                          %array
    out.slength = length(data);           %record data array length
    if (out.slength/3)>=2                 %if there is more than two
                                          %read points
        out.frequency(1:out.slength) = data(1,1:out.slength);%extract
                                                    %frequency data
        out.slevel(1:out.slength) =data(2,1:out.slength);%extract
                                                %signal level data
        out.dbm(1:out.slength) =data(3,1:out.slength);   %extract
                                             %signal level in dBm
    else %if there is only one read point
        out.frequency(1)= data(1,1);
        out.slevel(1) =data(2,1);
        out.dbm(1) =data(3,1);
    end;

    fclose(fid); %close data file

end;
```

APPENDIX D

2004 International Symposium on Electromagnetic Compatibility Excellent Award


EMC'04 Sendai

2004 International Symposium on Electromagnetic Compatibility, Sendai

Excellent Award

Kent Chamberlin and Maxim Khankin

For the paper entitled "Measuring the Impact of In-Vehicle-Generated EMI on VHF Radio Reception in an Unshielded Environment" presented at the EMC'04/Sendai held in Senda Japan on June 1-4, 2004 in recognition of the outstanding contribution to the conference.

杉浦行

Akira Sugiura

Conference Chairperson, EMC'04/Sendai

JUNE 2004

Figure D.1. 2004 International Symposium on Electromagnetic Compatibility Excellent Award